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Dynamics, Adaptive Backstepping Control and Circuit Implementation of Sprott MO_5 Chaotic System

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ABSTRACT

This research work discusses the qualitative properties of Sprott MO_5 chaotic system. The Lyapunov exponents of the Sprott MO_5 chaotic system are obtained as $L_1 = 0.1387$, $L_2 = 0$, and $L_3 = -0.8373$. Since the sum of the Lyapunov exponents is negative, the Sprott MO_5 chaotic system is dissipative. Also, the Kaplan-Yorke dimension of the Sprott MO_5 chaotic system is obtained as $D_{KY} = 2.1657$. The Sprott MO_5 chaotic system have three unstable equilibrium points on the x–axis. The phase portraits of the Sprott MO_5 chaotic system are simulated using MATLAB. Next, an adaptive backstepping controller is designed to stabilize the Sprott MO_5 chaotic system with unknown parameters. MATLAB simulations have been shown to illustrate and validate all the main results derived in this work. An electronic circuit realization of the Sprott MO_5 chaotic system is presented in details. Finally, the circuit experimental results of the Sprott MO_5 chaotic attractor show agreement with the numerical simulations.

Keywords: Chaos, chaotic systems, Sprott MO_5 chaotic system, adaptive control, circuit simulation.

1. INTRODUCTION

Chaotic systems are defined as nonlinear dynamical systems which are very sensitive to initial conditions, topologically mixing and also with dense periodic orbits [1].

The sensitivity to initial conditions of a chaotic system is indicated by a positive Lyapunov exponent. A dissipative chaotic system is characterized by the condition that the sum of the Lyapunov exponents of the chaotic system is negative.

Since Lorenz discovered a 3-D chaotic system of a weather model [2], great interest has been shown in the chaos literature in the analysis and modelling of many 3-D chaotic systems such as Rössler system [3], Rabinovich system [4], ACT system [5], Sprott systems [6], Chen system [7], Lü system [8], Shaw system [9], Feeny system [10], Shimizu system [11], Liu-Chen system [12], Cai system [13], Tigan system [14], Colpitt's oscillator [15], WINDMI system [16], Zhou system [17], etc.

Recently, many 3-D chaotic systems have been discovered such as Li system [18], Elhadj system [19], Pan system [20], Sundarapandian system [21], Yu-Wang system [22], Sundarapandian-Pehlivan system [23], Zhu system [24], Vaidyanathan systems [25-44], Tacha system [45], Vaidyanathan-Madhavan system [46], Pehlivan system [47], Jafari system [48], Pham system [49-50], etc.

Chaos theory has many important applications in science and engineering such as dynamo systems [51-55], Tokamak [56-57], oscillators [58-65], lasers [66], robotics [67], chemical reactors [68-75], biology [76-90], ecology [91], cardiology [92], memristors [93-94], artificial neural networks [95-96], text encryption [97], image encryption [98], voice encryption [99], secure communication systems [100-105], etc.

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Chaos control and chaos synchronization are important research problems in the chaos theory. In the last three decades, many mathematical methods have been developed successfully to address these research problems.

The study of control of a chaotic system investigates methods for designing feedback control laws that globally or locally asymptotically stabilize or regulate the outputs of a chaotic system.

Many methods have been developed for the control and tracking of chaotic systems such as active control [106-110], adaptive control [111-117], backstepping control [118-120], sliding mode control [121, 122], etc.

The synchronization of chaotic systems has applications in secure communications [123-125], cryptosystems [126-127], encryption [128-130], etc.

In the chaos literature, many different methodologies have been also proposed for the synchronization and anti-synchronization of chaotic systems such as PC method [131], active control [132-142], time-delayed feedback control [143,144], adaptive control [145-156], sampled-data feedback control [157-160], backstepping control [161-170], sliding mode control [171-176], etc.

In Section 2, we discuss the dynamics and qualitative properties of the Sprott MO_5 jerk chaotic system. The Lyapunov exponents of the Sprott MO_5 chaotic system are obtained as $L_1 = 0.1387$, $L_2 = 0$, and $L_3 = -0.8373$. Since the sum of the Lyapunov exponents of the Sprott MO_5 jerk chaotic system is negative, we deduce that the Sprott MO_5 chaotic system is dissipative. Also, the Kaplan-Yorke dimension of the Sprott MO_5 chaotic system is obtained as $D_{KY} = 2.1657$. The Sprott MO_5 chaotic system have three unstable equilibrium points on the $x-$axis. The phase portraits of the Sprott MO_5 chaotic system are simulated using MATLAB.

In Section 3, an adaptive backstepping controller is designed to stabilize the Sprott MO_5 jerkchaotic system with unknown parameters. MATLAB simulations have been shown to illustrate and validate all the main results derived in this work. In Section 4, an electronic circuit realization of the Sprott MO_5 jerkchaotic system is presented in detail. The circuit experimental results of the Sprott MO_5 jerk chaotic attractor show agreement with the numerical simulations. Finally, Section 5 concludes the paper with a summary.

2. DYNAMICS AND ANALYSIS OF SPROTT MO_5 CHAOTIC SYSTEM

The dynamics of the Sprott MO_5 jerk chaotic system [177] is described as follows.

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= z \\ \dot{z} &= -az - by + x - x^3 \end{aligned} \tag{1}$$

where x, y, z are the states and a, b are positive parameters.

The Sprott MO_5 jerk chaotic system (1) depicts a *chaotic attractor* when the parameter values are taken as follows:

$$a = 0.7, \quad b = 1 \tag{2}$$

For numerical simulations, we take the initial conditions of the Sprott MO_5 jerk chaotic system (1) as

$$x(0) = 0, \quad y(0) = 0, \quad z(0) = 0.1 \tag{3}$$

The 3-D portrait of the Sprott MO_5 jerk chaotic system (1) for the parameter values (2) and the initial conditions (3) is depicted in Figure 1.

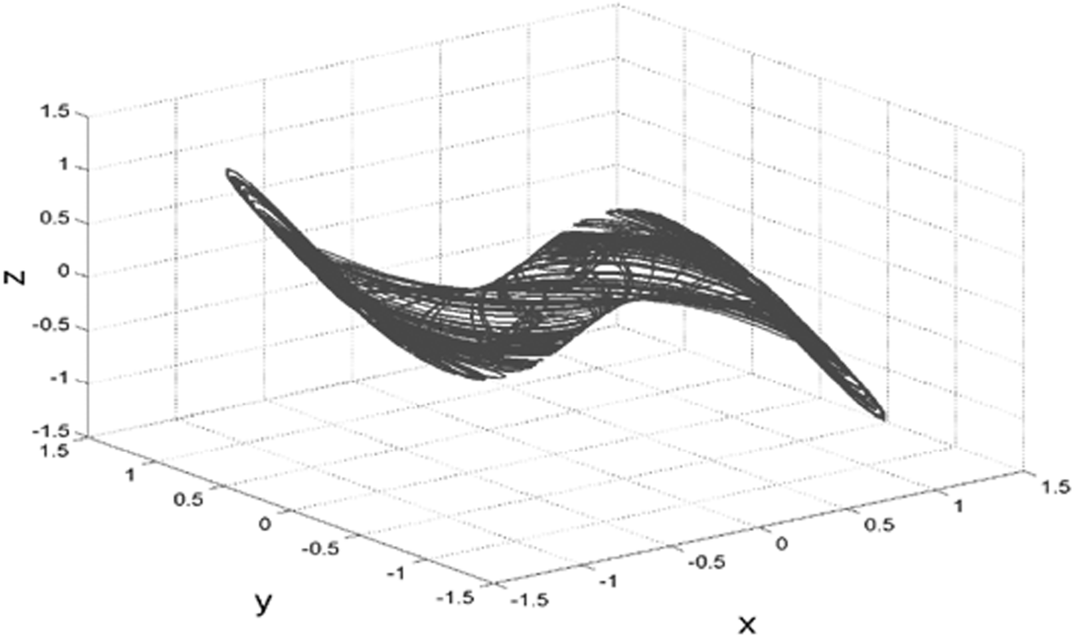


Figure 1: The chaotic attractor of the Sprott MO_5 chaotic system in R^3

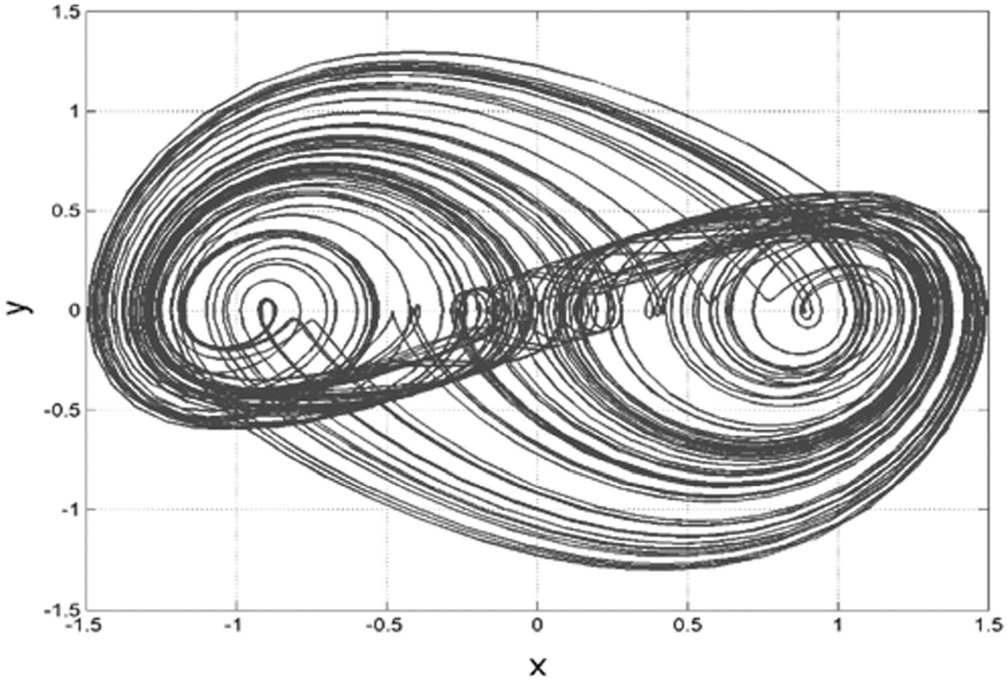


Figure 2: The 2-D projection of the Sprott MO_5 system on (x, y) plane

The 2-D portraits (projections on the three coordinate planes) of the Sprott MO_5 jerk chaotic system (1) are depicted in Figures 2-4.

The equilibrium points of the system (1) are obtained by solving the following system of equations with the parameter values as in the chaotic case (2):

$$\begin{cases} y = 0 \\ z = 0 \\ -az - by + x - x^3 = 0 \end{cases} \tag{4}$$

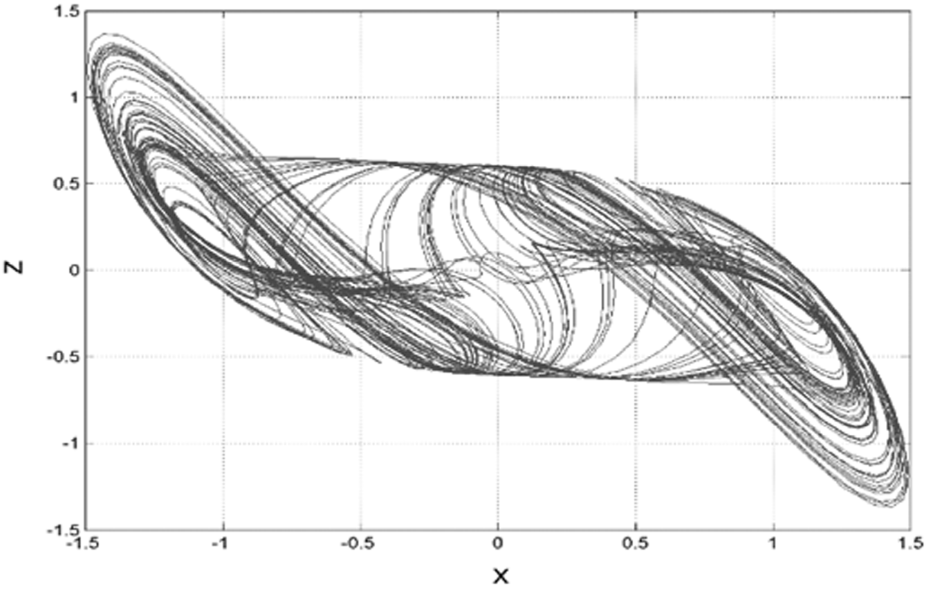


Figure 3: The 2-D projection of the Sprott MO_5 system on (x, z) plane

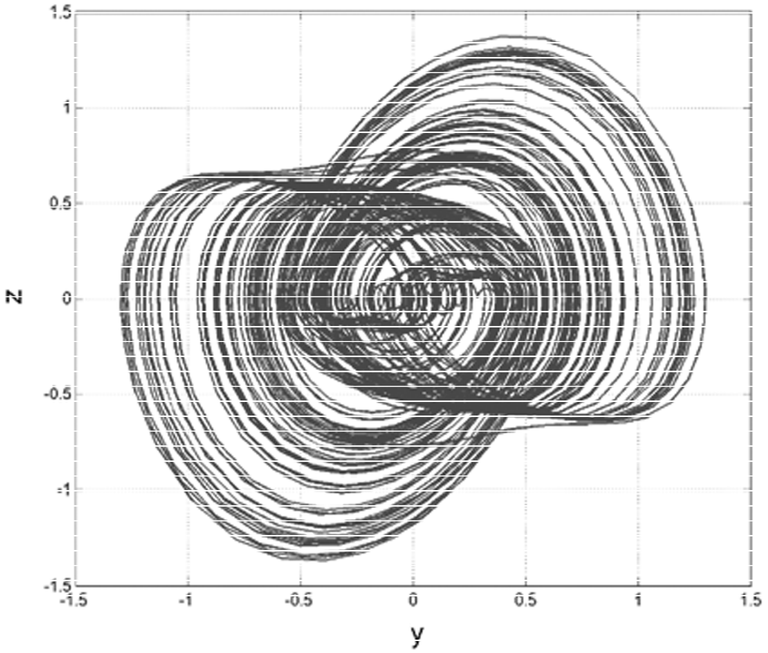


Figure 4: The 2-D projection of the Sprott MO_5 system on (y, z) plane

Solving (4), we obtain three equilibrium points of the Sprott MO_5 chaotic system (1), viz.

$$E_0 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad E_1 = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}, \quad E_2 = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

The Jacobian matrix of the system (1) is obtained as

$$J(x,y,z) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1-3x^2 & -1 & -0.7 \end{bmatrix} \tag{6}$$

Thus, the Jacobian matrix of (1) at E_0 is obtained as

$$J(E_0) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & -1 & -0.7 \end{bmatrix} \tag{7}$$

which has the eigenvalues

$$\lambda_1 = 0.5762, \quad \lambda_{2,3} = -0.6381 \pm 1.1525\, i \tag{8}$$

This shows that the equilibrium E_0 is a saddle-focus.

Next, the Jacobian matrix at E_1 is obtained as

$$J(E_1) = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -2 & -1 & -0.7 \end{bmatrix} \tag{9}$$

which has the eigenvalues

$$\lambda_1 = -1.2216, \quad \lambda_{2,3} = 0.2608 \pm 1.2527\, i \tag{10}$$

This shows that the equilibrium E_1 is a saddle-focus.

Since $J(E_1) = J(E_2)$, it is immediate that the equilibrium E_2 is also a saddle-focus.

Hence, all the three equilibrium points of the Sprott jerk chaotic system (1) are saddle-foci, which are unstable.

For the chosen parameter values (2), the Lyapunov exponents of the system (1) are numerically obtained using MATLAB as:

$$L_1 = 0.1387, \quad L_2 = 0, \quad L_3 = -0.8373 \tag{11}$$

Since the spectrum of Lyapunov exponents (11) has a positive term L_1 the system (1) is chaotic.

Also, the Maximal Lyapunov Exponent (MLE) of the jerk system (1) is calculated as $L_1 = 0.1387$.

Since the sum of the Lyapunov exponents is negative, the system (1) is dissipative.

Also, the Kaplan-Yorke dimension of the chaotic system (1) is calculated as:

$$D_{KY} = 2 + \frac{L_1 + L_2}{|L_3|} = 2.1657, \tag{12}$$

which is fractional.

Figure 5 depicts the Lyapunov exponents of the chaotic system (1).

4. ADAPTIVE CONTROL OF THE SPROTT MO_5 CHAOTIC SYSTEM

In this section, we construct an adaptive controller for globally stabilizing the unstable Sprott MO_5 jerk system with unknown parameters.

We consider the controlled Sprott MO_5 system

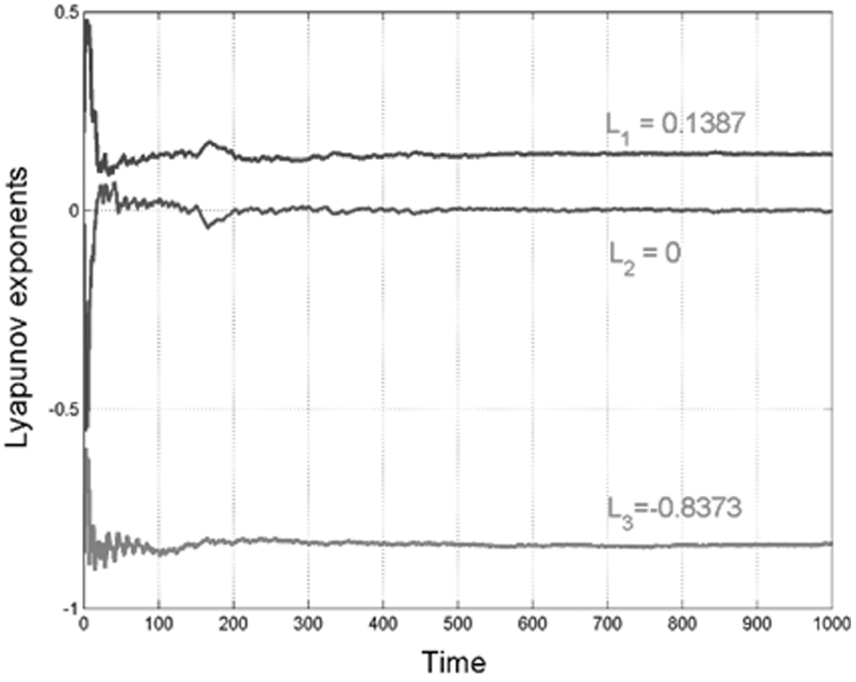


Figure 5: Lyapunov exponents of the Sprott MO$_5$ jerk chaotic system

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= z \\ \dot{z} &= -az - by + x - x^3 + u \end{aligned} \tag{13}$$

where x, y, z are state variables, a, b are unknown, constant, parameters and u is the adaptive backstepping control to be designed using estimates $A(t)$, $B(t)$ of the unknown parameters a, b, respectively.

We define the parameter estimation errors as

$$\begin{aligned} e_a(t) &= a - A(t) \\ e_b(t) &= b - B(t) \end{aligned} \tag{14}$$

Differentiating (14) with respect to we get

$$\begin{aligned} \dot{e}_a &= -\dot{A}(t) \\ \dot{e}_b &= -\dot{B}(t) \end{aligned} \tag{15}$$

Next, we shall state and prove the main result of this section.

Theorem 1. The Sprott MO$_5$ jerk system (13) with unknown parameters a and b is globally and exponentially stabilized by the adaptive feedback control law

$$u(t) = -4x - [5 - B(t)]y - [3 - A(t)]z + x^3 - k\eta_z \tag{16}$$

where $k > 0$ is a gain constant, with

$$\eta_z = 2x + 2y + z \tag{17}$$

and the update law for the parameter estimates is given by

$$\begin{aligned} \dot{A} &= -z\eta_z \\ \dot{B} &= -y\eta_z \end{aligned} \tag{18}$$

Proof. We prove this result via backstepping control method and Lyapunov stability theory [178].

First, we define a quadratic Lyapunov function

$$V_1(\eta_x) = \frac{1}{2}\eta_x^2 \tag{19}$$

where

$$\eta_x = x \tag{20}$$

Differentiating V_1 along the dynamics (13), we obtain

$$\dot{V}_1 = xy = -\eta_x^2 + \eta_x(x+y) \tag{21}$$

Now, we define

$$\eta_y = x + y \tag{22}$$

Using (22), we can simplify (21) as

$$\dot{V}_1 = -\eta_x^2 + \eta_x\eta_y \tag{23}$$

Next, we define a quadratic Lyapunov function

$$V_2(\eta_x, \eta_y) = V_1(\eta_x) + \frac{1}{2}\eta_y^2 = \frac{1}{2}\left(\eta_x^2 + \eta_y^2\right) \tag{24}$$

Differentiating V_2 along the dynamics (13), we get

$$\dot{V}_2 = -\eta_x^2 - \eta_y^2 + \eta_y(2x + 2y + z) \tag{25}$$

Now, we define

$$\eta_z = 2x + 2y + z \tag{26}$$

Using (26), we can simplify (25) as

$$\dot{V}_2 = -\eta_x^2 - \eta_y^2 + \eta_y\eta_z \tag{27}$$

Finally, we define a quadratic Lyapunov function

$$V\left(\eta_x, \eta_y, \eta_z, e_a, e_b\right) = \frac{1}{2}\left(\eta_x^2 + \eta_y^2 + \eta_z^2 + e_a^2 + e_b^2\right) \tag{28}$$

Differentiating V along the dynamics (13), we get

$$\dot{V} = -\eta_x^2 - \eta_y^2 - \eta_z^2 + \eta_z S - e_a\dot{A} - e_b\dot{B} \tag{29}$$

where

$$S = \eta_z + \eta_y + \dot{\eta}_z = \eta_z + \eta_y + 2\dot{x} + 2\dot{y} + \dot{z} \tag{30}$$

Simplifying the equation (30), we get

$$S = 4x + (5-b)y + (3-a)z - x^3 + u \tag{31}$$

Substituting (16) into (31), we get

$$S=-[b-B(t)]y-[a-A(t)]z-k\eta_z \tag{32}$$

Using (14), we can simplify (32) as

$$S=-e_b y-e_a z-k\eta_z \tag{33}$$

Substituting (33) into (29), we get

$$\dot{V}=-\eta_x^2-\eta_y^2-(1+k)\eta_z^2+e_a\left[-z\eta_z-\dot{A}\right]+e_b\left[-y\eta_z-\dot{B}\right] \tag{34}$$

Substituting (18) into (34), we obtain

$$\dot{V}=-\eta_x^2-\eta_y^2-(1+k)\eta_z^2 \tag{35}$$

Thus, it is clear that $\dot{V}$ is a negative semi-definite function on R^3.

From (35), it follows that $\eta(t)=(\eta_x(t), \eta_y(t), \eta_z(t))$ and the parameter estimation vector $(e_a(t), e_b(t))$ are globally bounded, i.e.

$$\left[\eta(t) \quad e_a(t) \quad e_b(t)\right]\in L_\infty \tag{36}$$

Also, it follows from (35) that

$$\dot{V}\le -\eta_x^2-\eta_y^2-\eta_z^2=-\|\eta(t)\|^2 \tag{37}$$

That is,

$$\|\eta(t)\|^2\le -\dot{V} \tag{38}$$

Integrating the inequality (38) from 0 to t, we get

$$\int_0^t \|\eta(\tau)\|^2 d\tau \le V(0)-V(t) \tag{39}$$

From (39), it follows that $\eta(t)\in L_2$.

Using (13), we can conclude that $\dot{\eta}\in L_\infty$.

Thus, using Barbalat's lemma [178], we conclude that $\eta(t)\to 0$ exponentially as $t\to\infty$ for all initial conditions $\eta(0)\in R^3$. Thus, it follows that $x(t)\to 0$, $y(t)\to 0$ and $z(t)\to 0$ exponentially as $t\to\infty$ for all initial conditions in R^3.

This completes the proof. ■

For numerical simulations, the parameter values of the Sprott MO_5 system (13) are taken as in the chaotic case, *viz*. $a = 0.7$ and $b = 1$. We take the gain constant as $k = 10$.

The initial conditions of theSprott MO_5 chaotic system (13) are taken as $x(0) = 8.3$, $y(0) = 6.2$ and $z(0) = -14.5$.

The initial conditions of the parameter estimates are taken as $A(0) = 15.7$ and $B(0) = 5.9$.

Figure 6 describes the time-history of the state vector $(x(t), y(t), z(t))$ of the controlled Sprott MO_5 jerk system (13).

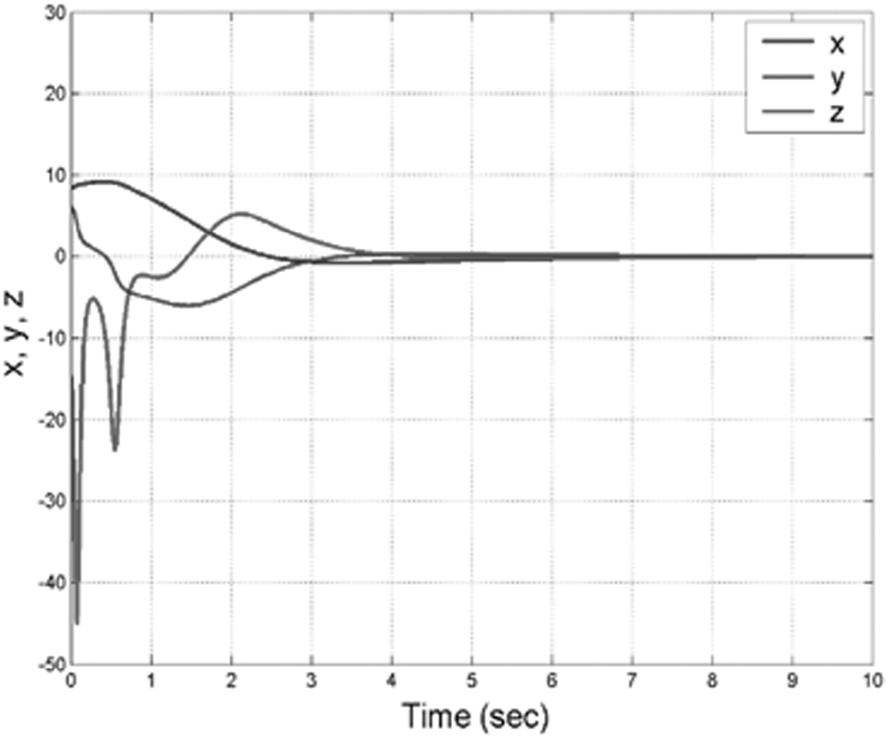


Figure 6:Time-history of the controlled state of the MO_5 system (13)

5. CIRCUIT REALIZATION OF THE SPROTT MO_5 CHAOTIC SYSTEM

In this section, we design an electronic circuit modeling of the Sprott MO_5 jerk chaotic system (1). The circuit in Fig. 11 has been designed following an approach based on operational amplifiers [179-180] where the state variables x, y, z of the system (1) are associated with the voltages across the capacitors C_1, C_2 and C_3, respectively. The nonlinear term of system (1) are implemented with the analog multiplier. By applying Kirchhoff's laws to the designed electronic circuit, its nonlinear equations are derived in the following form:

$$\begin{cases} \dot{x} = \dfrac{1}{C_1R_1}y \\ \dot{y} = \dfrac{1}{C_2R_2}z \\ \dot{z} = -\dfrac{1}{C_3R_3}z - \dfrac{1}{C_3R_4}y + \dfrac{1}{C_3R_5}x - \dfrac{1}{100C_3R_6}x^3 \end{cases} \tag{40}$$

We choose the following:

$$R_1 = R_2 = R_4 = R_5 = R_7 = R_8 = 10k\Omega,\ R_6 = 100k\Omega$$
$$R_3 = 14.286k\Omega,\ R_9 = R_{10} = R_{11} = R_{12} = 10k\Omega,$$
$$C_1 = C_2 = C_3 = 10nF$$

The circuit has three integrators by using Op-amp TL082CD in a feedback loop and two multipliers IC AD633. The supplies of all active devices are $\pm 15V$.

With MultiSIM 10.0, we obtain the experimental observations of system (1) as shown in Figs. 11-13. As compared with Figs. 2-4, a good qualitative agreement between the numerical simulation and the MultiSIM 10.0 results of the Sprott MO_5 chaotic system is confirmed.

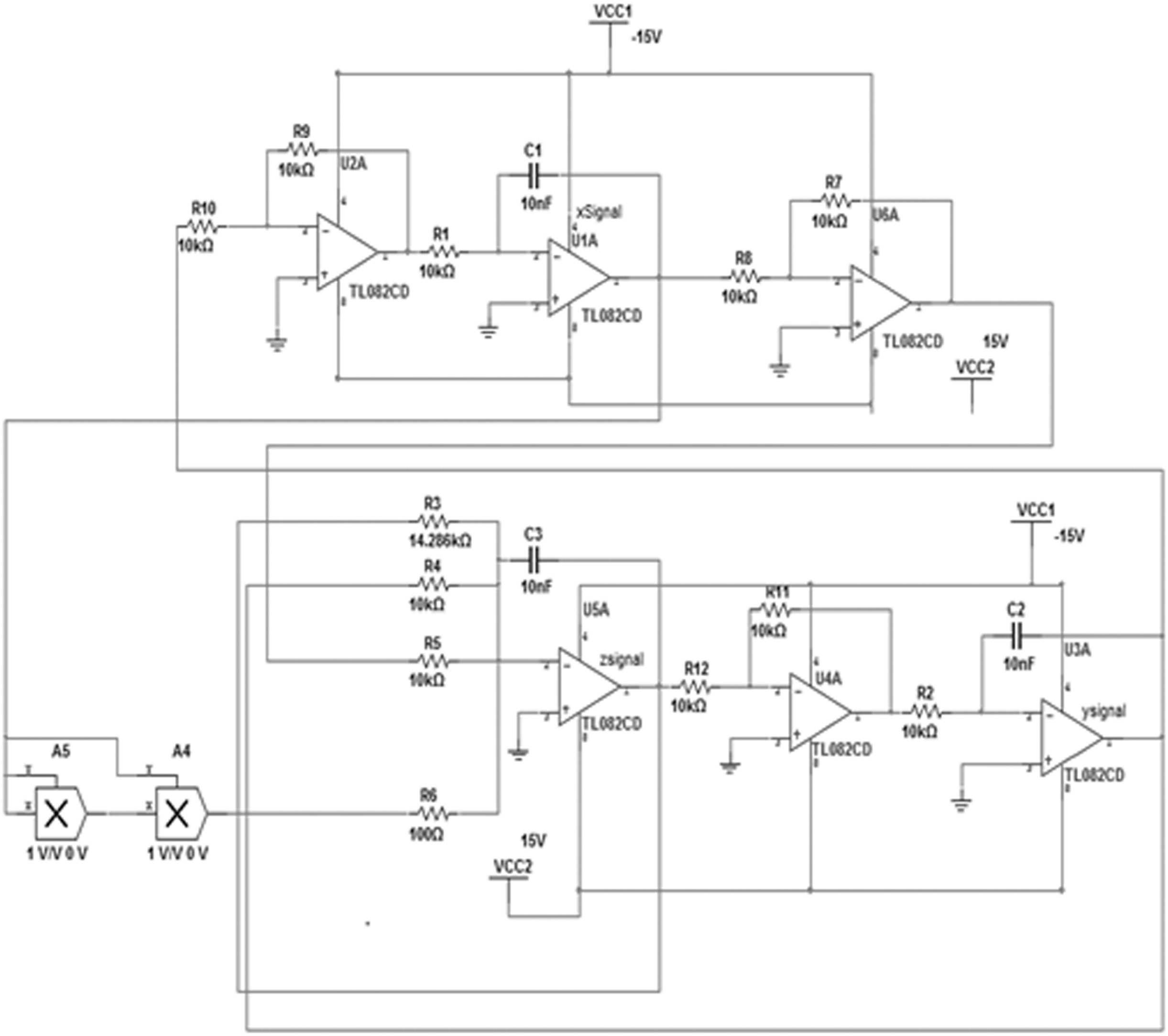
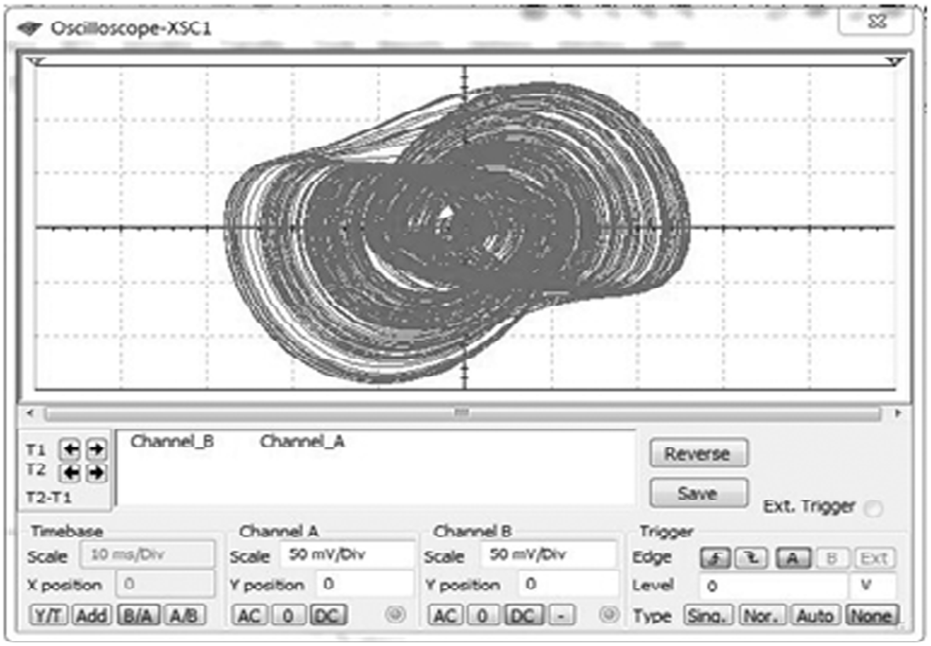


Figure 7: Circuit realization of the Sprott MO_5 chaotic system using MultiSIM 10.0


Oscilloscope-XSC1

T1
T2
T2-T1
Channel_B Channel_A

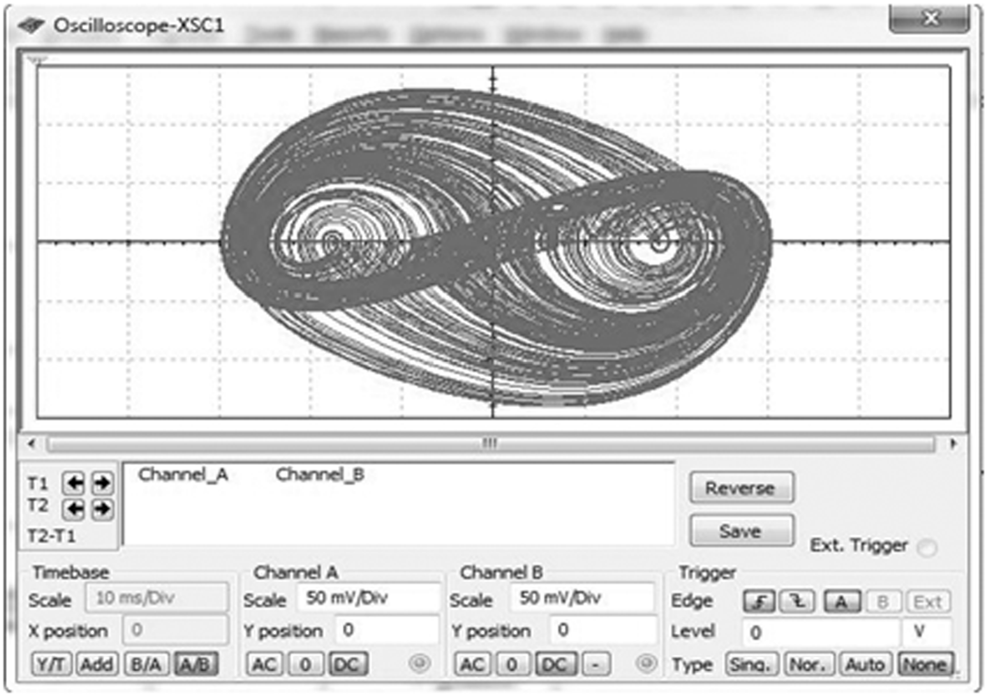
Timebase
Scale 10 ms/Div
X position 0

Channel A
Scale 50 mV/Div
Y position 0

Channel B
Scale 50 mV/Div
Y position 0

Trigger
Edge
Level 0 V

Figure 8: 2-D projection of the Sprott MO_5 chaotic system in *x*-*y* plane using MultiSIM 10.0



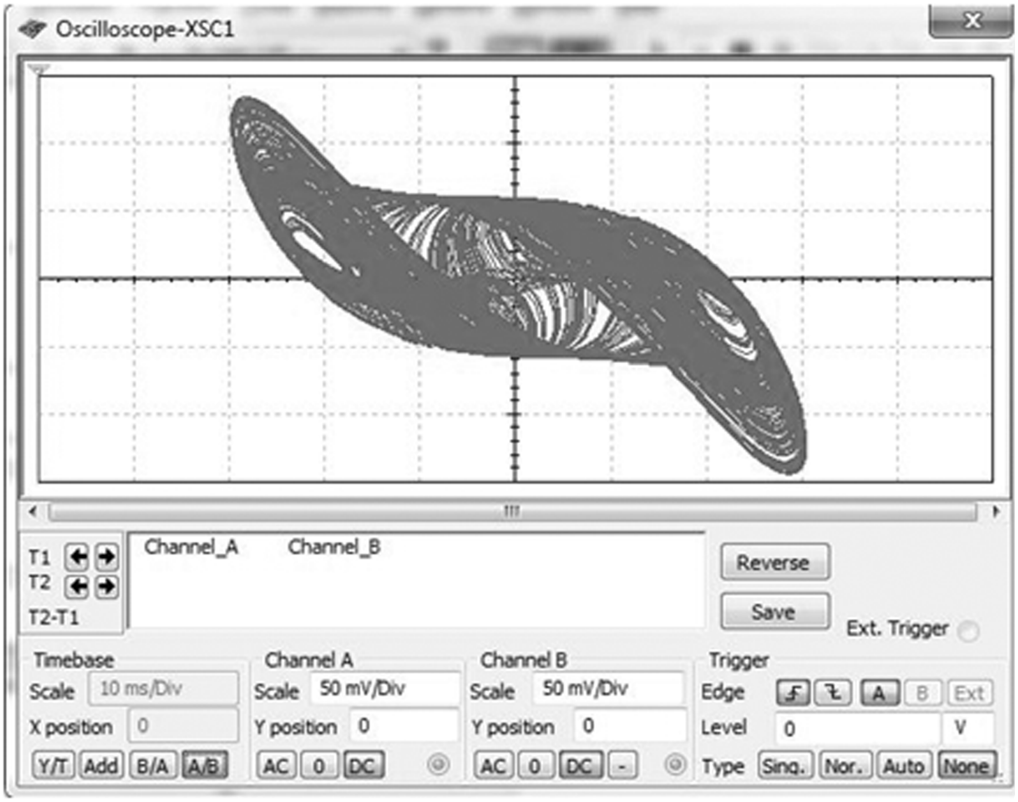
Timebase
Scale 10 ms/Div
X position 0

Channel A
Scale 50 mV/Div
Y position 0

Channel B
Scale 50 mV/Div
Y position 0

Trigger
Edge
Level 0 V
Type

Figure 9: 2-D projection of the Sprott MO_5 chaotic system in y-z plane using MultiSIM 10.0



Timebase
Scale 10 ms/Div
X position 0

Channel A
Scale 50 mV/Div
Y position 0

Channel B
Scale 50 mV/Div
Y position 0

Trigger
Edge
Level 0 V
Type

Figure 10: 2-D projection of the Sprott MO_5 chaotic system in x-z plane using MultiSIM 10.0

6. CONCLUSIONS

In this research work, we discussed the qualitative properties of Sprott chaotic system. Using backstepping control, we established new results for the adaptive control of the Sprott chaotic system. An electronic circuit realization of the Sprott chaotic system has been presented in detail that shows agreement of the circuit and numerical simulations for the Sprott chaotic system.

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